RECENT RESULTS FROM MINOS AND FUTURE PROSPECTS

Jonathan M. Paley for the MINOS Collaboration
Indiana University

Fermilab Users' Meeting
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The MINOS Collaboration

Argonne - Arkansas Tech - Athens - Benedictine - Brookhaven - Caltech - Cambridge - Campinas - Fermilab - Harvard - IIT - Indiana - Minnesota-Twin Cities - Minnesota-Duluth - Oxford - Pittsburgh - Rutherford - São Paulo - South Carolina - Stanford - Sussex - Texam A&M - Texas-Austin - Tufts - UCL - Warsaw - William & Mary
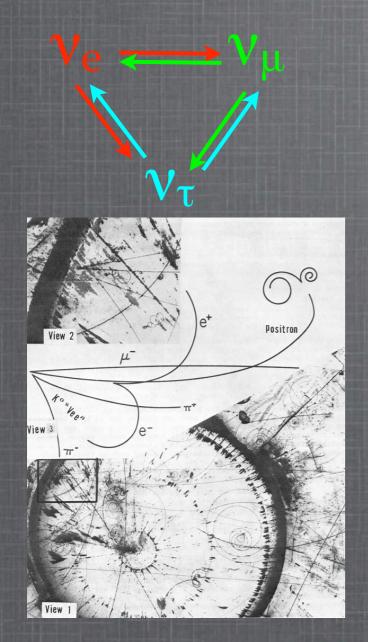
2007-08: Very Productive Year!

- 4 articles published or submitted to peer-reviewed journals
- 6 theses
- 2 boxes opened
- significant progress in understanding backgrounds and systematic uncertainties in all analyses

Outline of the Rest of this Talk

- **The MINOS Experiment**

- **What's new (2007-08)**

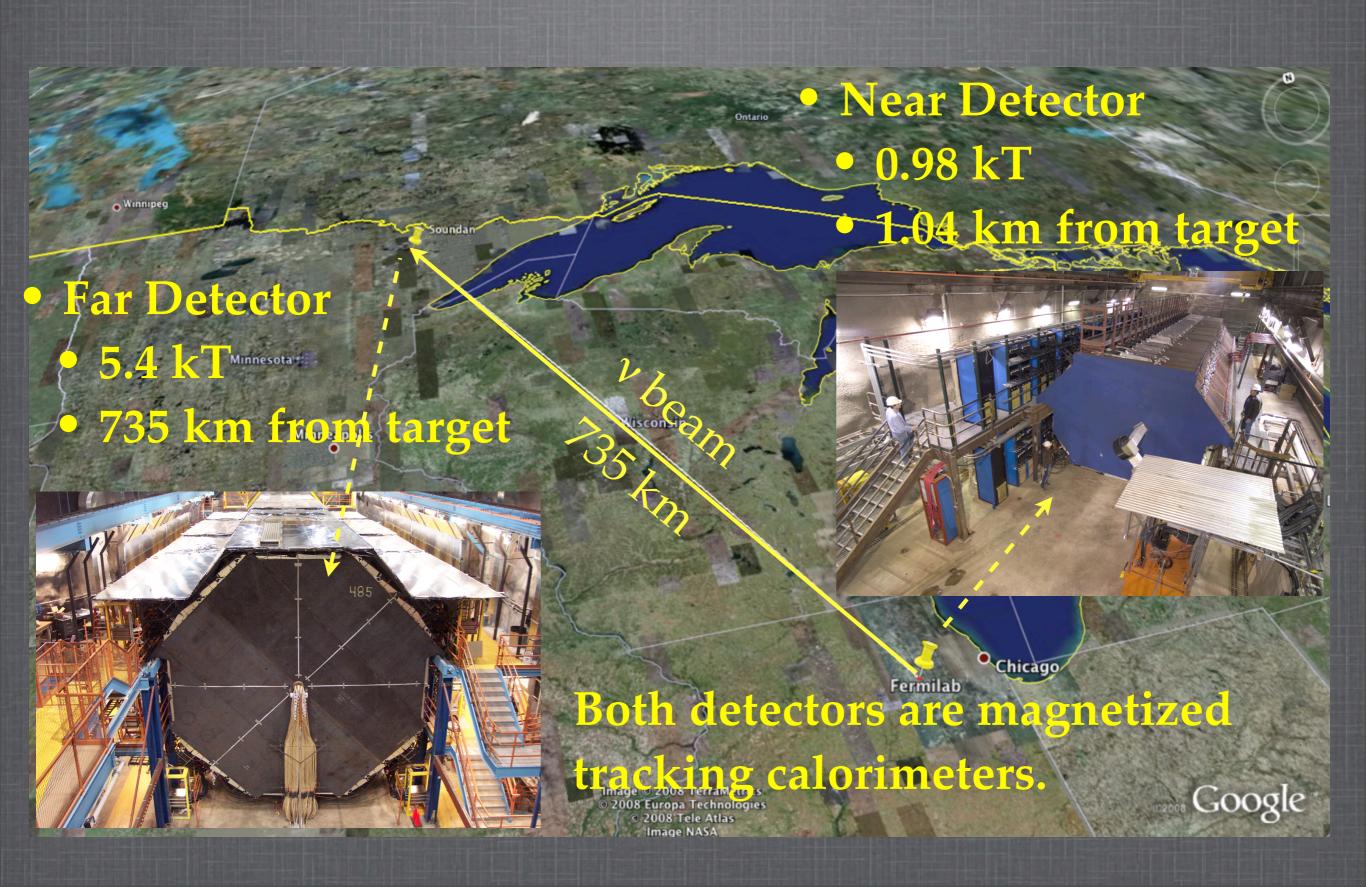- **Future Prospects**

Goals of the MINOS Experiment

ν_e ←→ ν_μ

ν_τ

- **Make precise measurement of Δm^2 and $\sin^2(2\theta)$**

  $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta) \sin^2(1.27 \, \Delta m^2 \, L/E)$

- **Confirm oscillations vs. other explanations (decay, decoherence)**
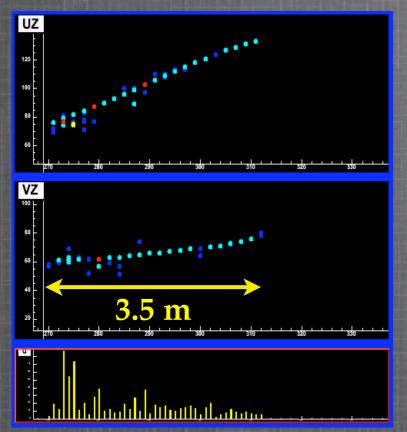
- **Search for subdominant $\nu_\mu \rightarrow \nu_e$**

- **CPT tests**
- **Search for sterile neutrinos**
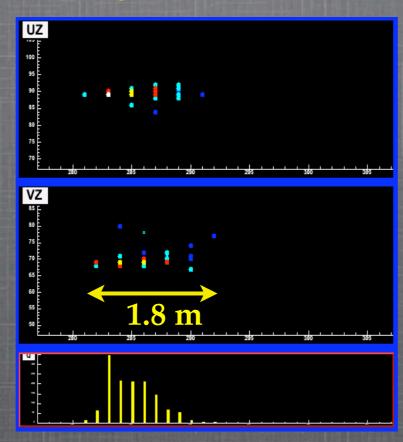- **Atmospheric neutrino and cosmic ray**

The MINOS Experiment

- **Near Detector**
- **0.98 kT**
- **1.04 km from target**

- **Far Detector**
- **5.4 kT**
- **735 km from target**

ν beam
735 km

Both detectors are magnetized tracking calorimeters.

Image © 2008 TerraMetrics
© 2008 Europa Technologies
© 2008 Tele Atlas
Image NASA

Google

Identifying Events in MINOS

ν_μ CC event

3.5 m
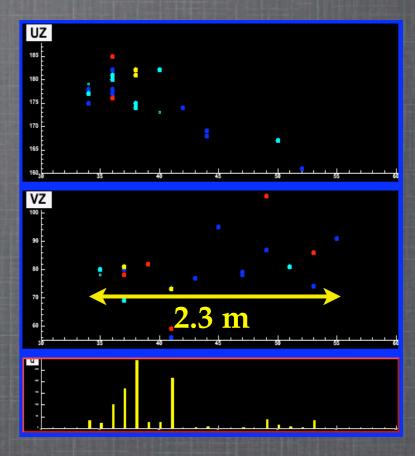
Long μ track +
shower at vertex

ν_e CC event

1.8 m

Short event with
EM shower profile.

NC event

2.3 m
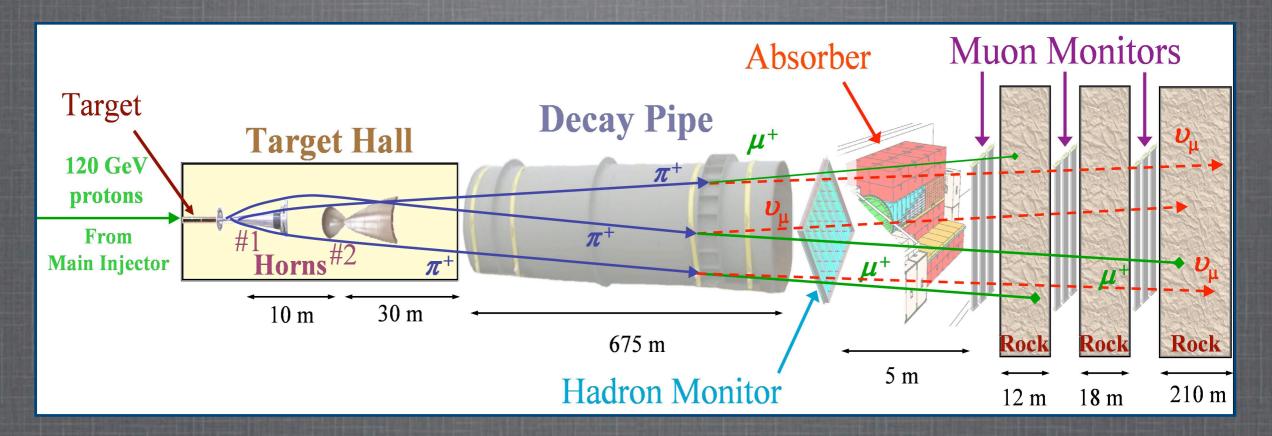
Short, diffuse event.

$$E_\nu = E_{shower} + E_{\mu,e}$$

$$\delta E_{shower} = 55\%/\sqrt{E} \qquad \delta E_\mu = 6\% \text{ range, } 10\% \text{ curvature}$$
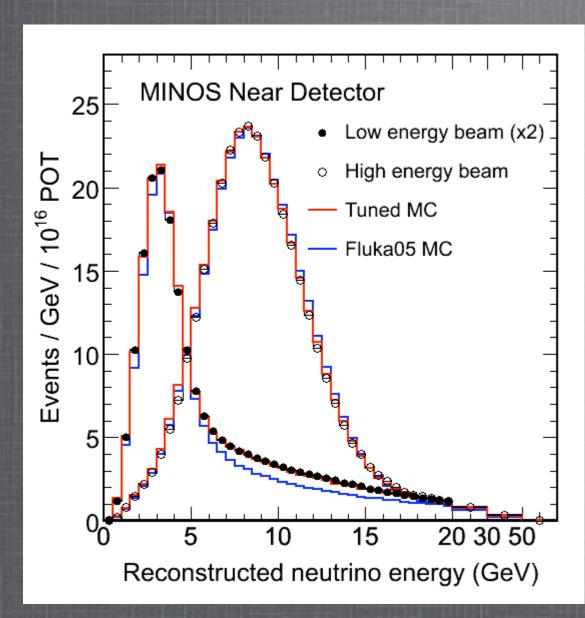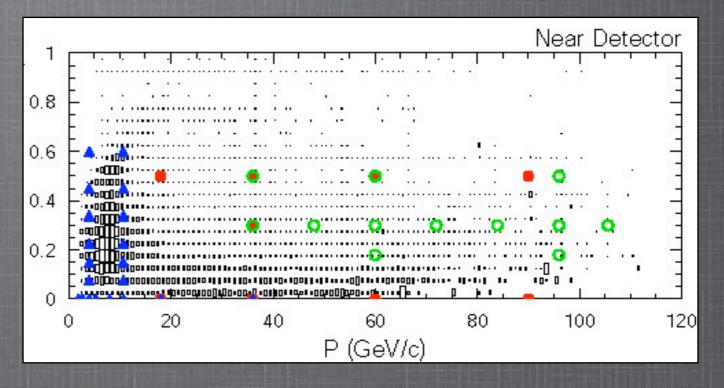
Producing Neutrinos at the Main Injector

- **Mesons produced in 120 GeV/c p + 165% λ_L graphite target interactions are focused in two magnetic horns.**
- **ν beam energy is *tunable* by moving target position longitudinally w.r.t. the horn positions.**
- **In LE beam configuration, beam is composed of 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, and 1.3% ν_e and $\overline{\nu}_e$.**
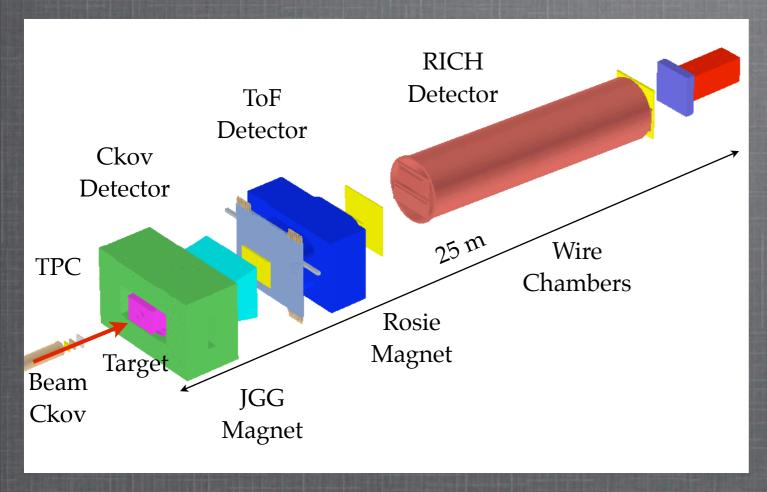
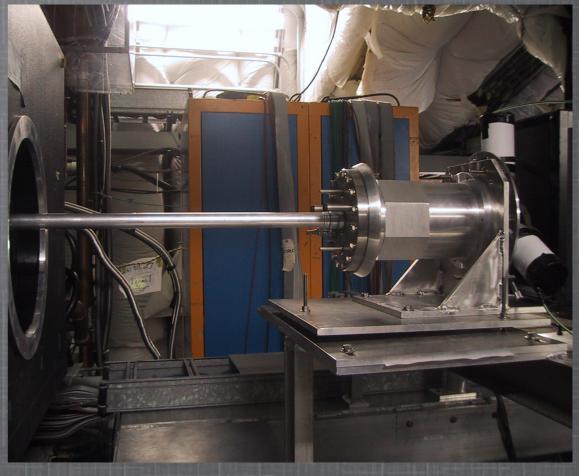# Predicting the Flux

- **MINOS uses Fluka06 MC to predict the ν flux.**
- **Uncertainty on flux is ~30% due to lack of hadron production data.**

- **To improve our data-to-MC agreement, we tune the Fluka MC to ND energy spectra of different beam configurations.**
- **These beam-reweighted spectra are used in all analyses discussed today.**
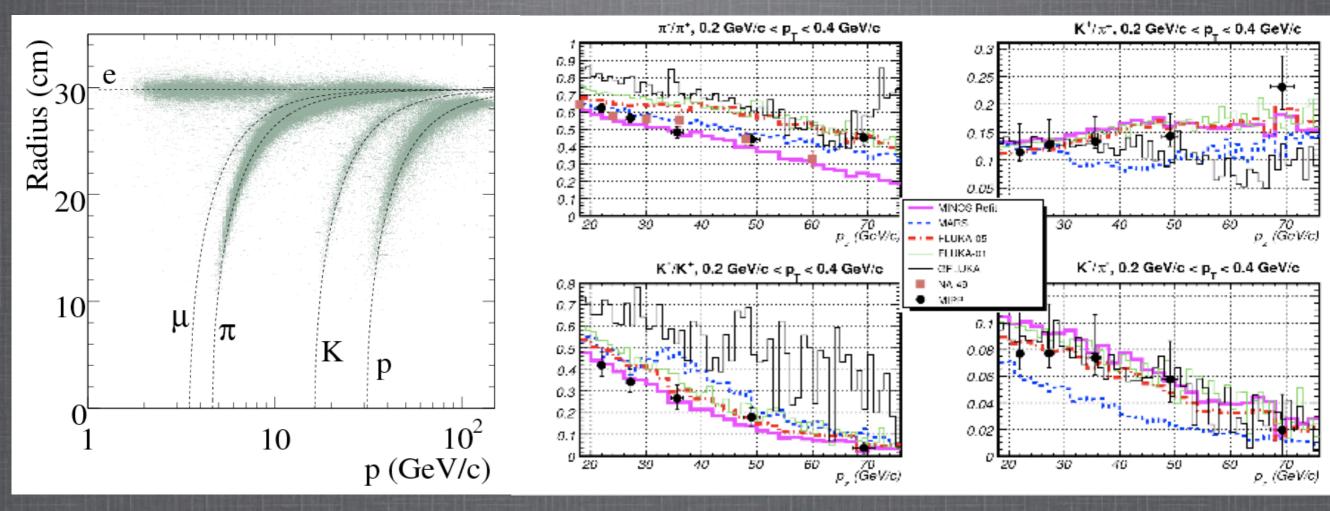
Measurement of Hadron Production off NuMI Target in MIPP
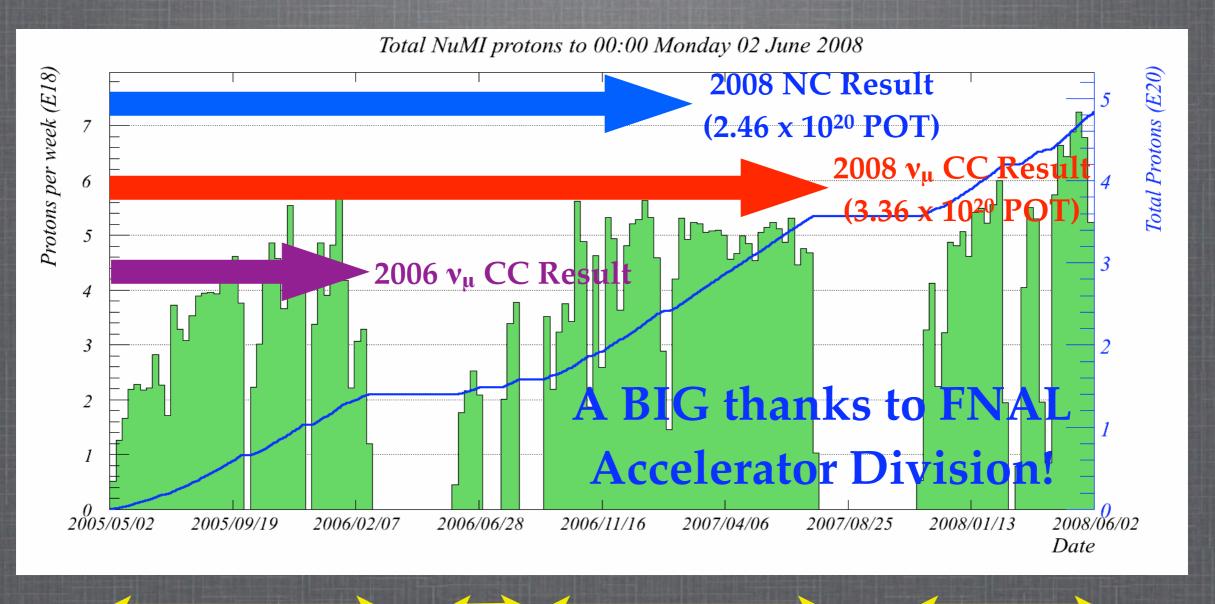

- **Main Injector Particle Production (MIPP) is a fixed target experiment with beams of π, K and p from 5-120 GeV/c and LH2, C, Be, Bi, U targets.**
- **MIPP has collected 1.6×10^6 events of 120 GeV p striking the MINOS target.**

Status of MIPP Analysis

- **π⁻/π⁺, K⁻/K⁺ , and K/π production ratios above 20 GeV/c agree well with expectations from MINOS beam-tuning.**
- **The MIPP Collaboration has completed the calibration of all PID detectors and is now focusing on the hadron production measurement from the NuMI target data set.**
- **See poster by Yusuf Gunaydin.**

NuMI Beam
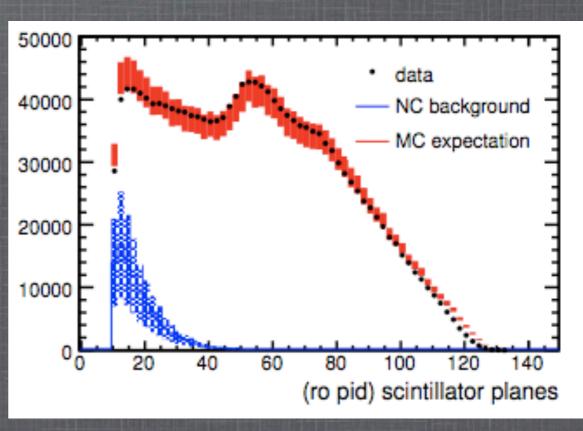
ν_μ CC Analysis

Precision measurement of Δm^2 and $\sin^2(2\theta)$
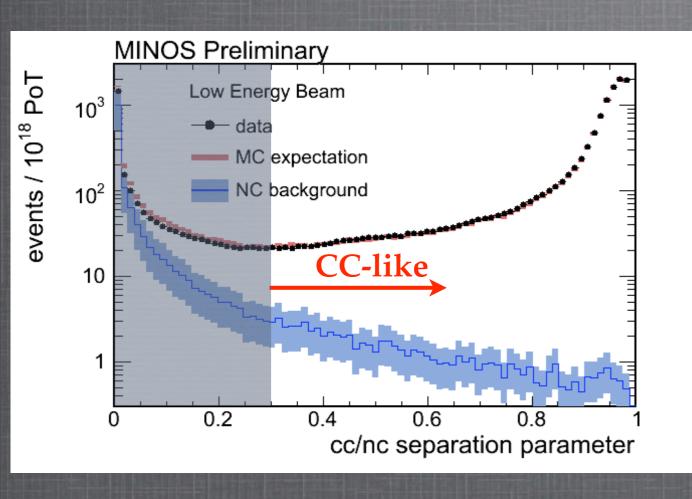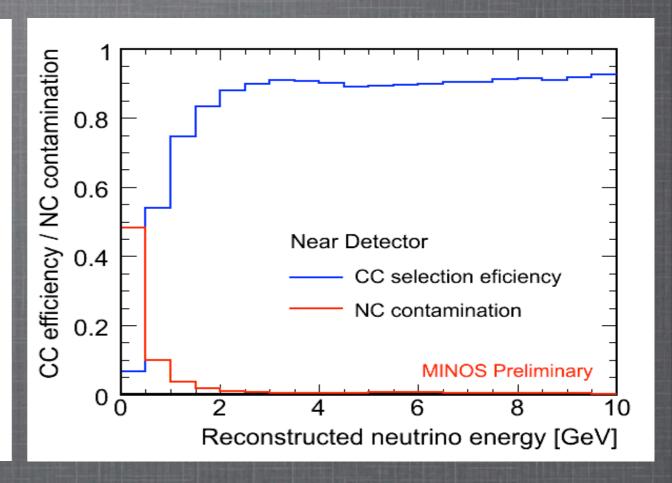
ν_μ CC Event Selection

- **Events must have:**
  - at least 1 reconstructed track
  - event vertex must fall within fiducial volume
  - track must be negative charge (no $\bar{\nu}_\mu$)
- **CC/NC separation achieved via a kNN event selection based on:**
  - Track length
  - Mean pulse height
  - Fluctuation in pulse height
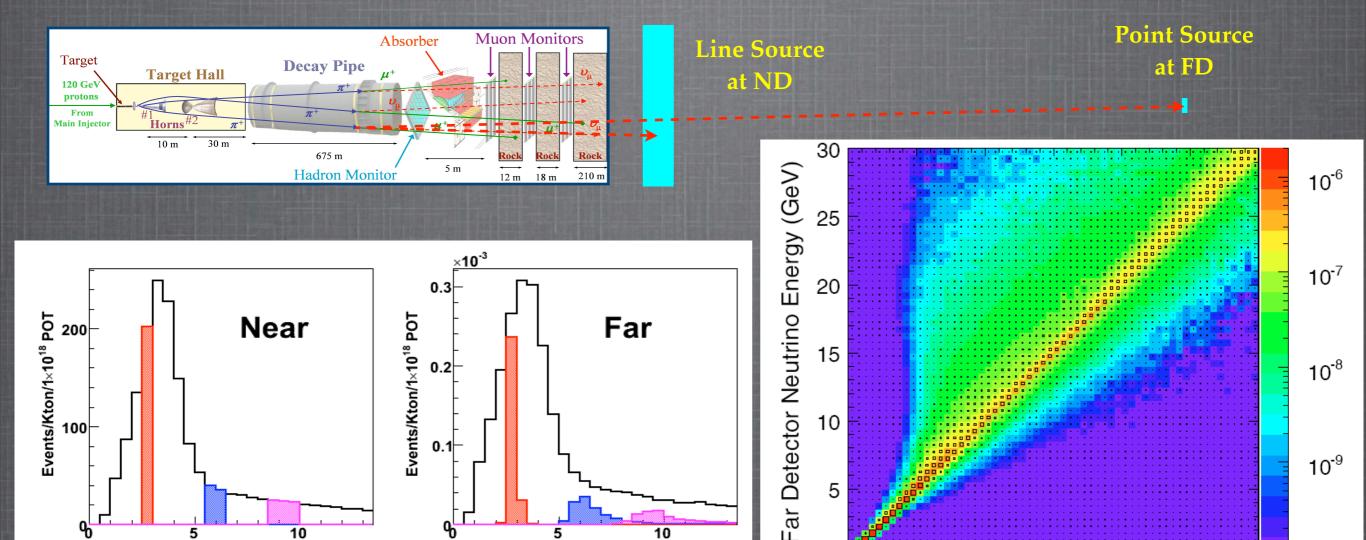 - Transverse track profile

ν_μ CC Event Selection

- **Cut on separation parameter maximizes CC selection efficiency and minimizes NC background.**
- **Good agreement between data and MC above the CC/NC separation parameter cut.**

Expected Far Detector Spectrum

- **Near detector spectrum is extrapolated to the far detector.**
- **Use MC to provide energy smearing and acceptance corrections.**

Systematic Uncertainties

- **Systematic uncertainties estimated by fitting modified MC in place of data.**
- **ν_μ CC measurement is statistics limited.**
- **Dominant uncertainties are:**
  - **ND/FD relative normalization (Δm^2)**
  - **Overall hadronic energy calibration (Δm^2)**
  - **NC background ($\sin^2(2\theta)$)**
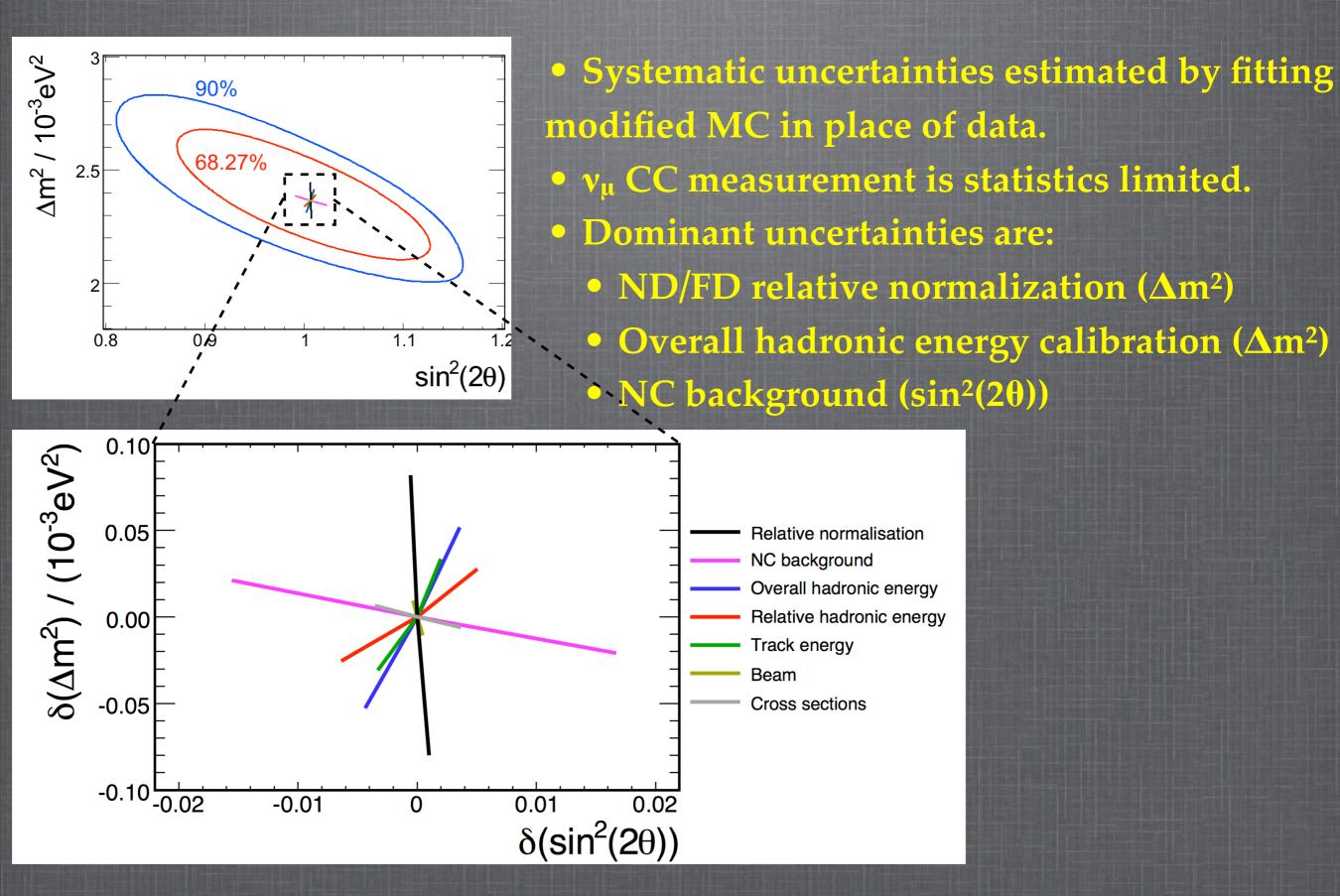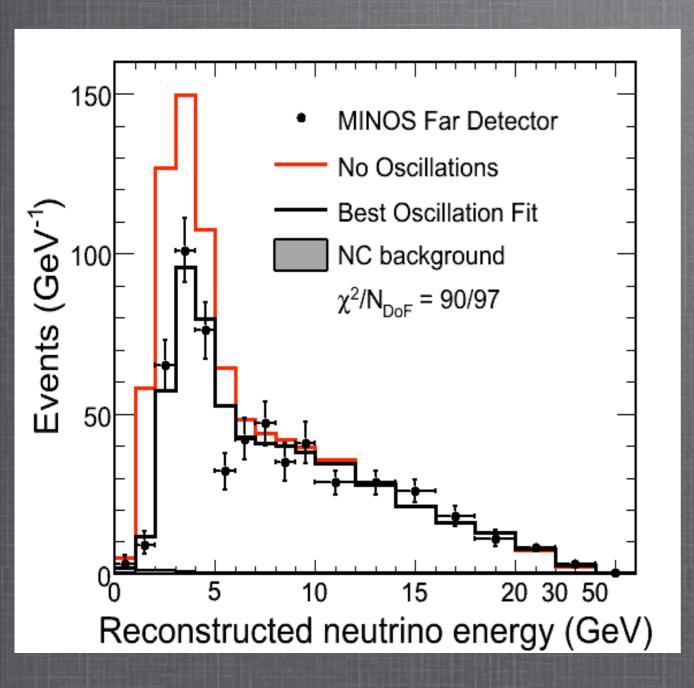
FD Energy Spectrum/Performing the Fit

MINOS Far Detector
No Oscillations
Best Oscillation Fit
NC background
$\chi^2/N_{DoF} = 90/97$

Events (GeV^{-1}) vs Reconstructed neutrino energy (GeV)
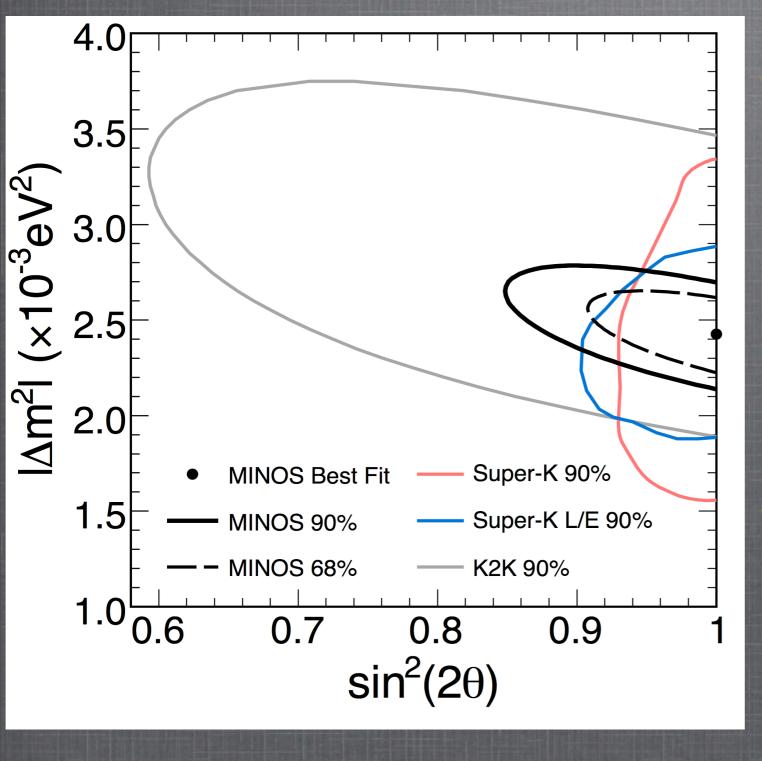
Best fit:

$\Delta m^2 = 2.43 \times 10^{-3}$ eV^2

$\sin^2(2\theta) = 1.00$

- FD energy spectrum is only looked at after performing:
  - low-level data quality checks
  - procedural checks
- 848 events observed in the FD
- 1065 ± 60 expected with no oscillations
- We fit the energy distribution to the oscillation hypothesis:

$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L/E)$

- The three largest systematic uncertainties are included as nuisance parameters
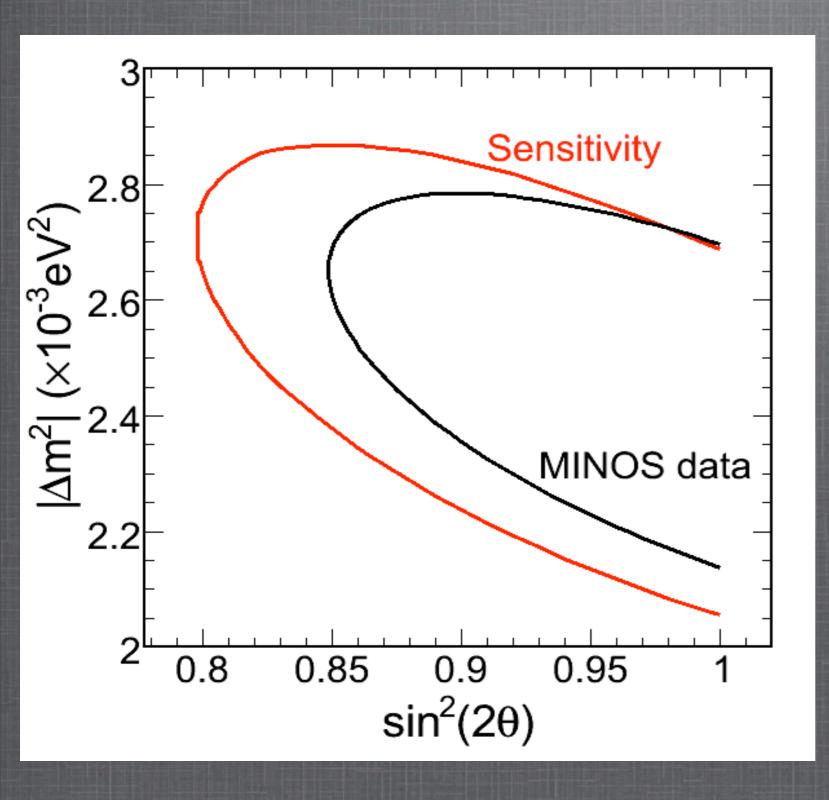- $\sin^2(2\theta)$ is constrained to be ≤ 1.

Contours

- **Constrained fit:**
  - $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL)
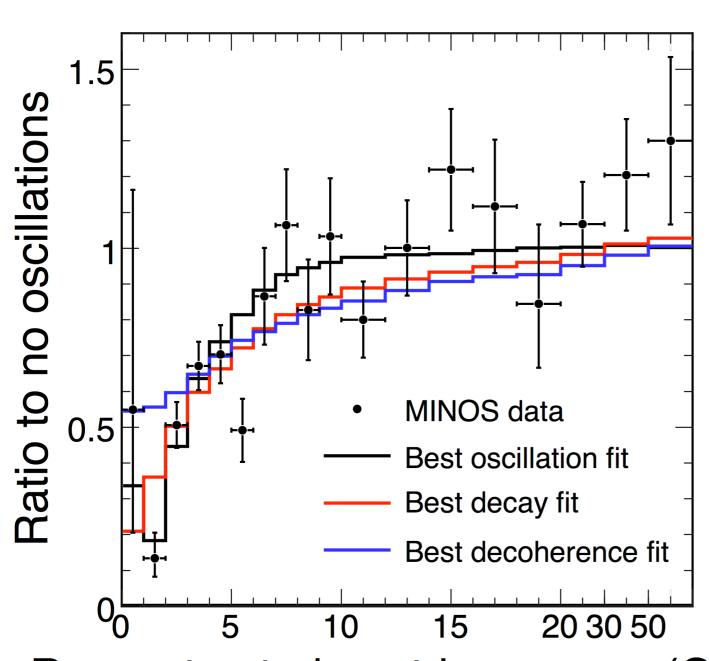 - $\sin^2(2\theta) > 0.90$ (90% CL)
  - $\chi^2/ndof = 90/97$

- **Unconstrained fit:**
  - $\Delta m^2 = 2.33 \times 10^{-3}$ eV^2
  - $\sin^2(2\theta) = 1.07$
  - $\Delta\chi^2 = -0.6$

Sensitivity

- **Final contour is a bit smaller than the predicted sensitivity because $\sin^2(2\theta)$ falls in the unphysical region.**
- **A study shows that 26.5% of unconstrained fits have a fit value of $\sin^2(2\theta) \geq 1.07$**
- **Feldman-Cousins study indicates that our contours are slightly conservative.**

Alternative Hypotheses

Decay:

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \exp(-\alpha L/E)$$

$$\chi^2/\text{ndof} = 104/97$$
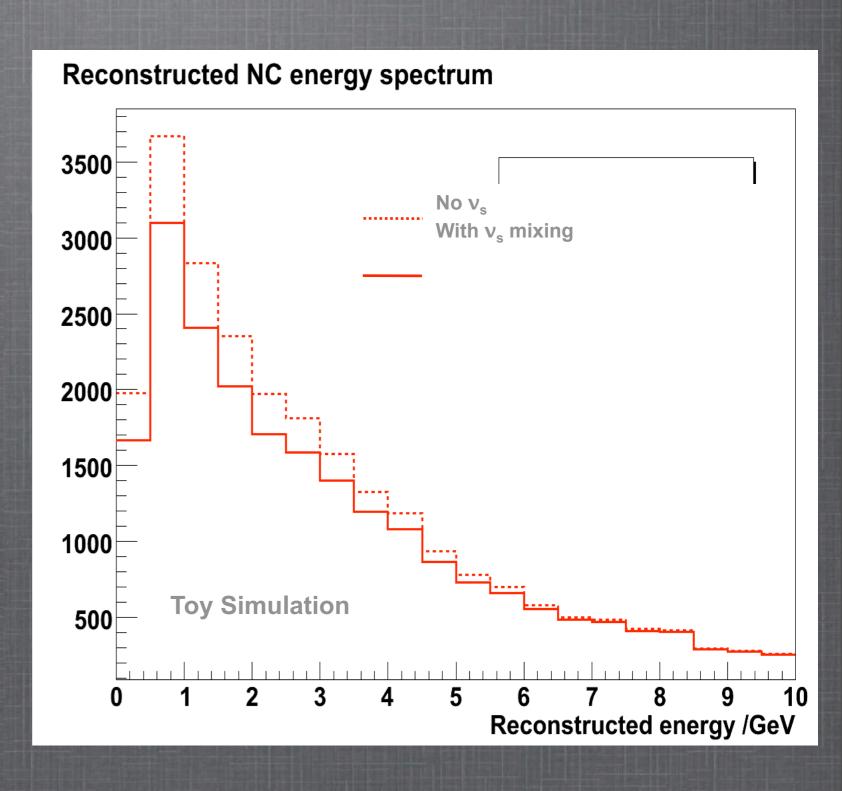
$$\Delta\chi^2 = 14$$

Disfavored at 3.7 σ

Decoherence:

$$P_{\mu\mu} = 1 - \tfrac{1}{2} \sin^2(2\theta) (1 - \exp(-\mu^2 L/2E))$$

$$\chi^2/\text{ndof} = 123/97$$

$$\Delta\chi^2 = 33$$

Disfavored at 5.7 σ

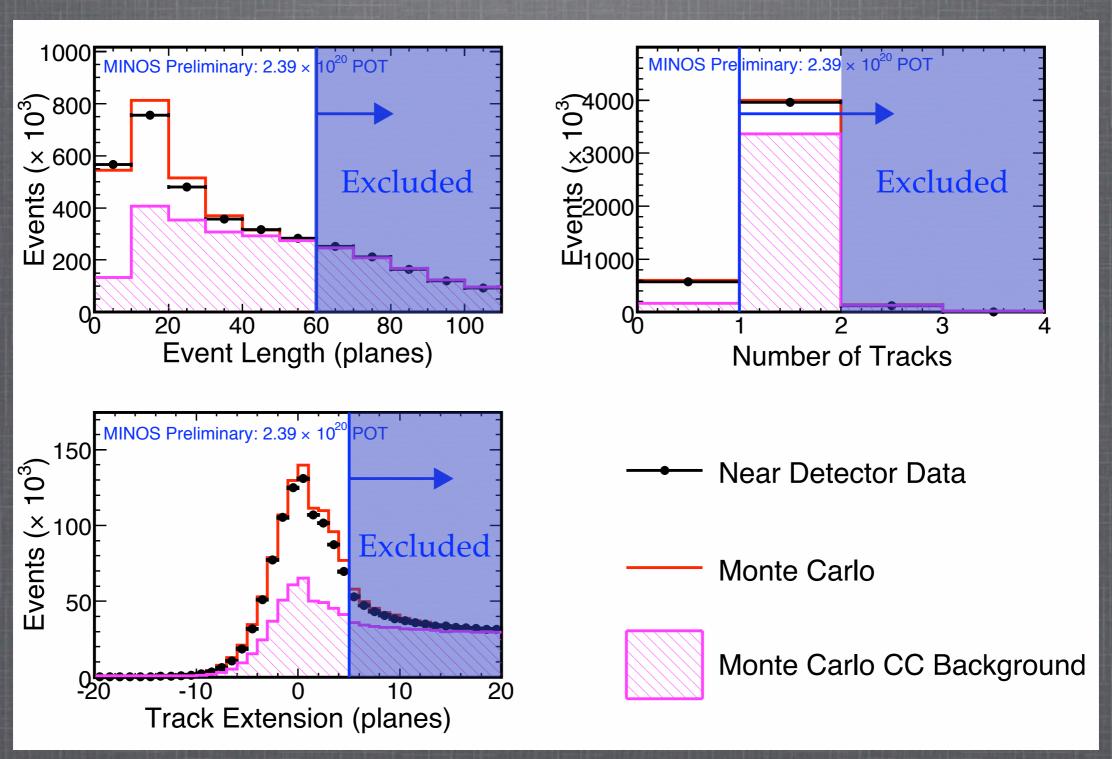# NC Analysis

The search for sterile neutrinos

Why NC Events?

- **Oscillations of ν_μ into ν_s would result in a depletion of both CC and NC events in the FD.**
- **Depletion of CC events could be masked by $\nu_\mu \Rightarrow \nu_\tau$. Depletion of NC events can only be explained by ν_s, since NC events are "flavor-blind".**

Reconstructed NC energy spectrum

No ν_s
With ν_s mixing
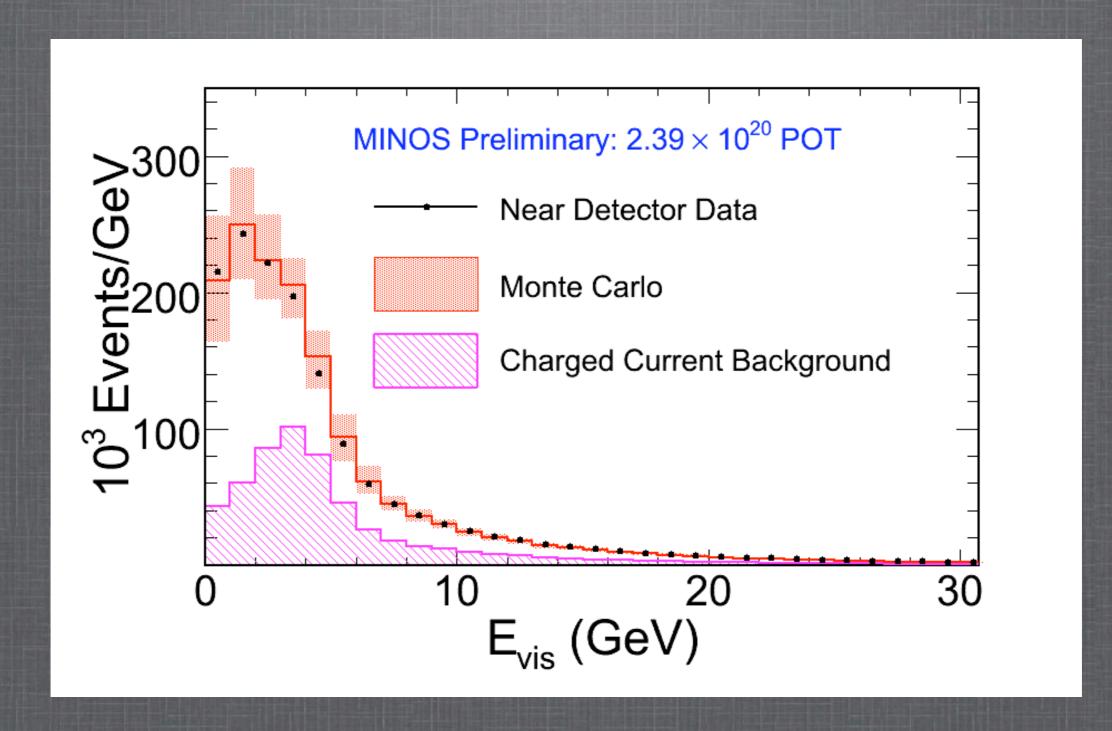
Toy Simulation

Reconstructed energy /GeV

NC Event Selection in the ND

Select reconstructed "shower-like" events that fall within a fiducial volume.

Expected Far Detector Spectrum

MINOS Preliminary: 2.39×10^{20} POT

- Near Detector Data
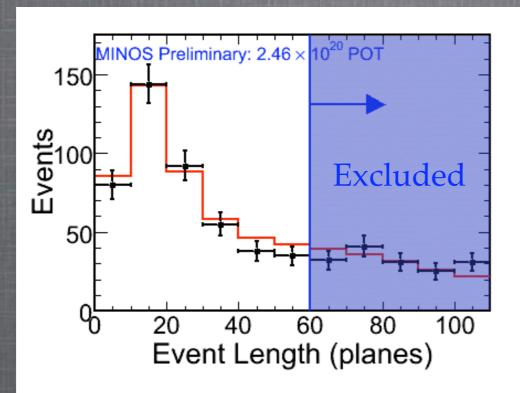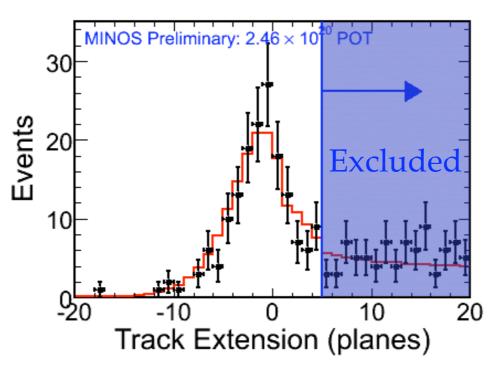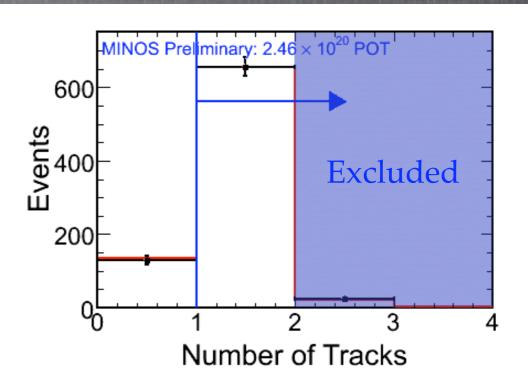- Monte Carlo
- Charged Current Background

10^3 Events/GeV vs E_{vis} (GeV)

NC event selection efficiency is 90%, purity is 60%.

NC Event Selection in the FD

- **Identical cuts are made in FD as in ND.**
- **MC oscillated with 2007 MINOS CC best fit values of $\Delta m^2 = 2.38 \times 10^{-3}$ eV^2 and $\sin^2(2\theta) = 1$.**
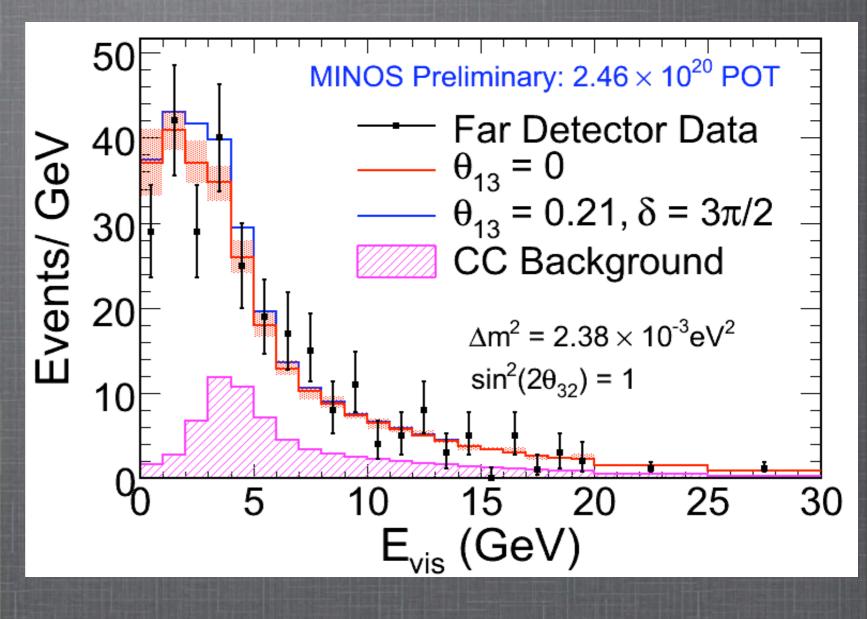
3-Flavor Analysis Results

- $\Delta m^2_{32} = 2.38 \times 10^{-3} \text{ eV}^2$

- $\Delta m^2_{21} = 7.59 \times 10^{-5} \text{ eV}^2$

- $\sin^2(2\theta_{12}) = 0.61$ ← KamLAND + SNO

- $\sin^2(2\theta_{23}) = 1$

- $\theta_{13} = 0 \text{ or } 0.21$ ← CHOOZ limit normal MH, $\delta = 3\pi/2$

Data/MC Comparison for $\theta_{13} = 0$

Energy Range (GeV)	0 - 3	0 - 5	0 - 120
Data	100	165	291
MC	115.16 ± 7.67	175.92 ± 10.42	292.63 ± 15.02
Significance (σ)	1.15	0.65	0.10

MINOS Preliminary: 2.46×10^{20} POT

— Far Detector Data
— $\theta_{13} = 0$
— $\theta_{13} = 0.21, \delta = 3\pi/2$
CC Background

$\Delta m^2 = 2.38 \times 10^{-3} \text{eV}^2$
$\sin^2(2\theta_{32}) = 1$

- **For $E_{vis} < 3$ GeV, $f_s < 35\%$ at 90% CL.**

- **For $E_{vis} < 120$ GeV, $f_s < 17\%$ at 90% CL.**
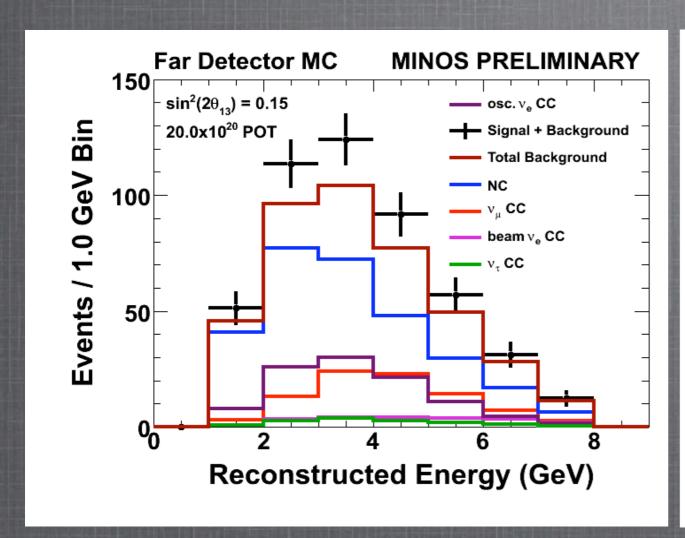
Other Finalized Analyses

- **"Sudden stratospheric warmings seen by an underground detector"**: correlation between FD cosmic muon rate and temperature changes in the upper atmosphere.

- **"Testing Lorentz Invariance and CPT Conservation with MINOS Near Detector Neutrinos"**: search for a sidereal signal in the MINOS ND.   Upper limits set on individual SME Lorentz and CPT violating terms.

- **"Observation of deficit in NuMI neutrino-induced rock and non-fiducial muons in MINOS far detector and measurement of neutrino oscillation parameters"**: see poster by Aaron McGowan

ν_e CC Analysis
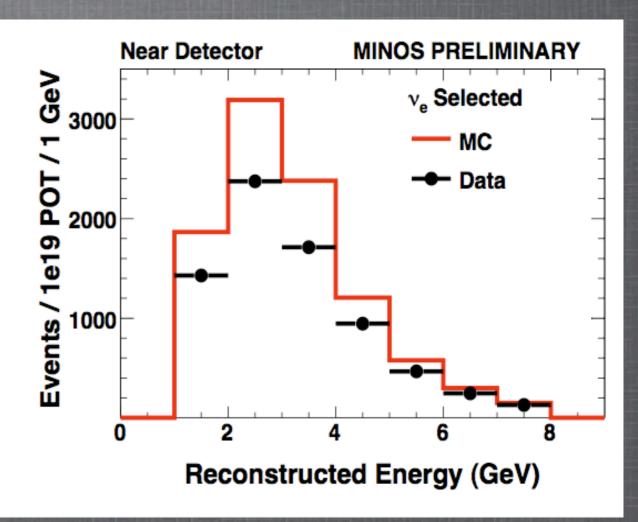
The search for ν_e appearance

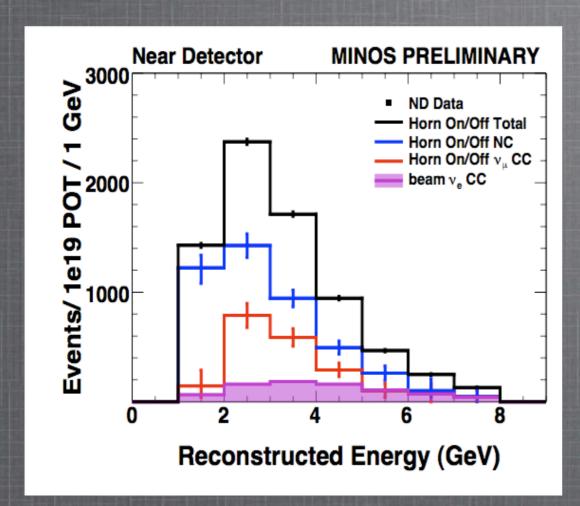**** See posters by Steven Cavanaugh and Lisa Whitehead for more details!**
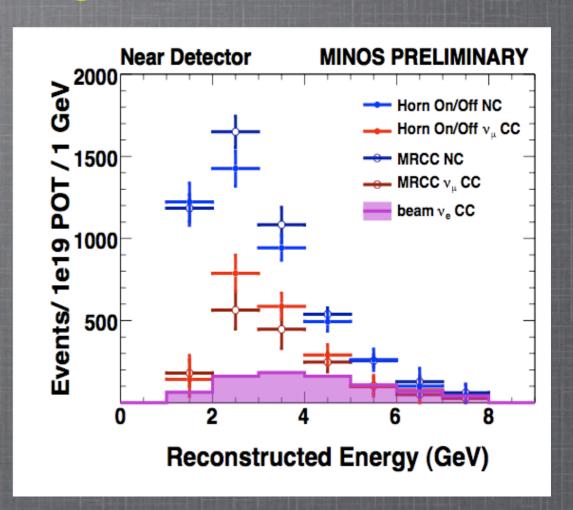
ν_e Background Estimates

- **Measurement dominated by backgrounds: at the CHOOZ limit, 12 ν_e events are expected with 42 background events (for 3.25 x 10^{20} POT).**
- **Dominant backgrounds are NC and high-y ν_μ CC events.**
- **We see a very large discrepancy between selected ν_e ND MC and data events.**

ν_e Data-Driven Background Studies
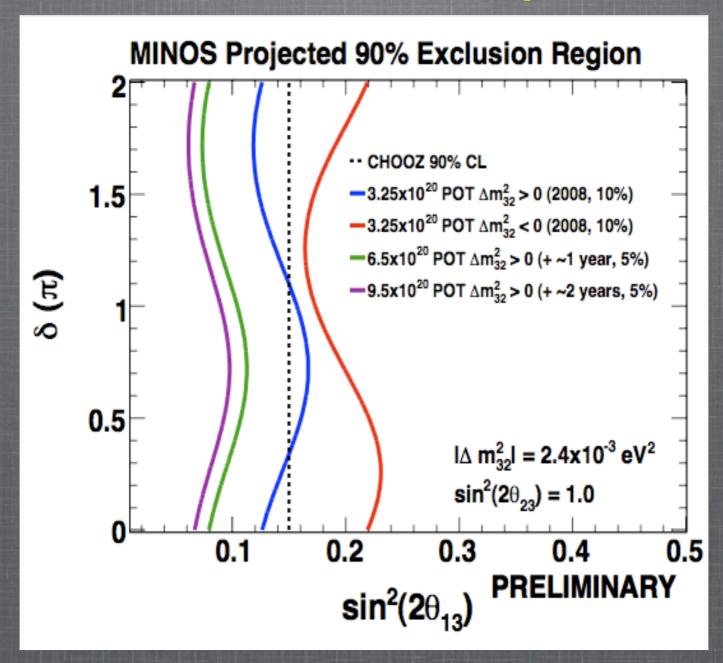
Estimate	Signal ν_e	Total BG	NC	ν_μ CC	Beam ν_e	ν_τ CC
Horn On/Off	12	42	29	8	3	2
MRCC	12	43	32	6	3	2

$\sin^2(2\theta_{23}) = 1.0$
$\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$
$\sin^2(2\theta_{13}) = 0.15$
no matter effects
3.25×10^{20} POT

- Horn On/Off - constrain the relative ratios of NC and ν_μ CC background events in two different beam configurations.
- Muon removed hadron showers from ν_μ CC (MRCC).

ν_e Sensitivity
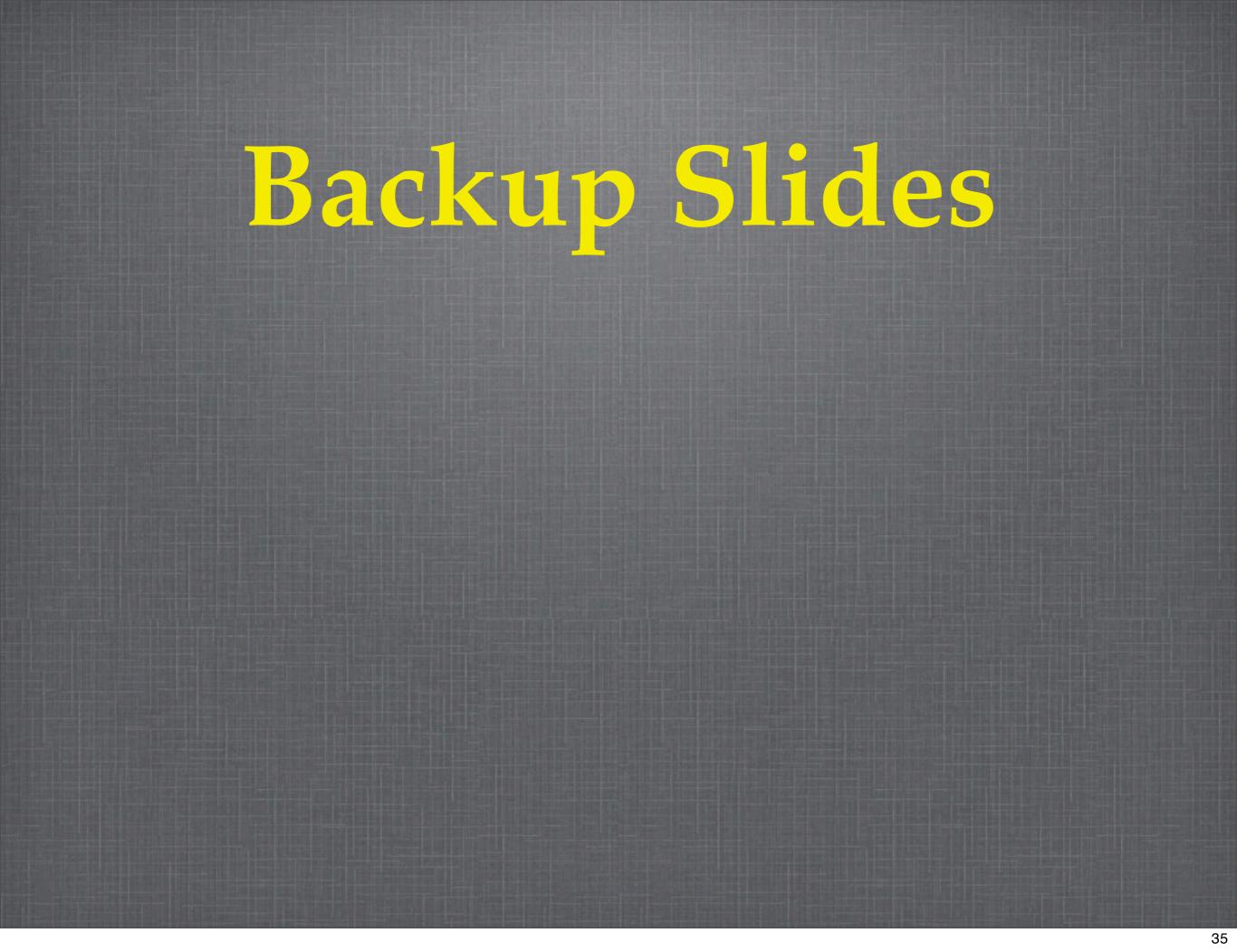
- **Projected limits for expected MINOS integrated exposures for the next few years.**
- **Inverted hierarchy (in red) shown only for lowest exposure.**
- **MINOS can improve upon the CHOOZ limit by ~x2.**
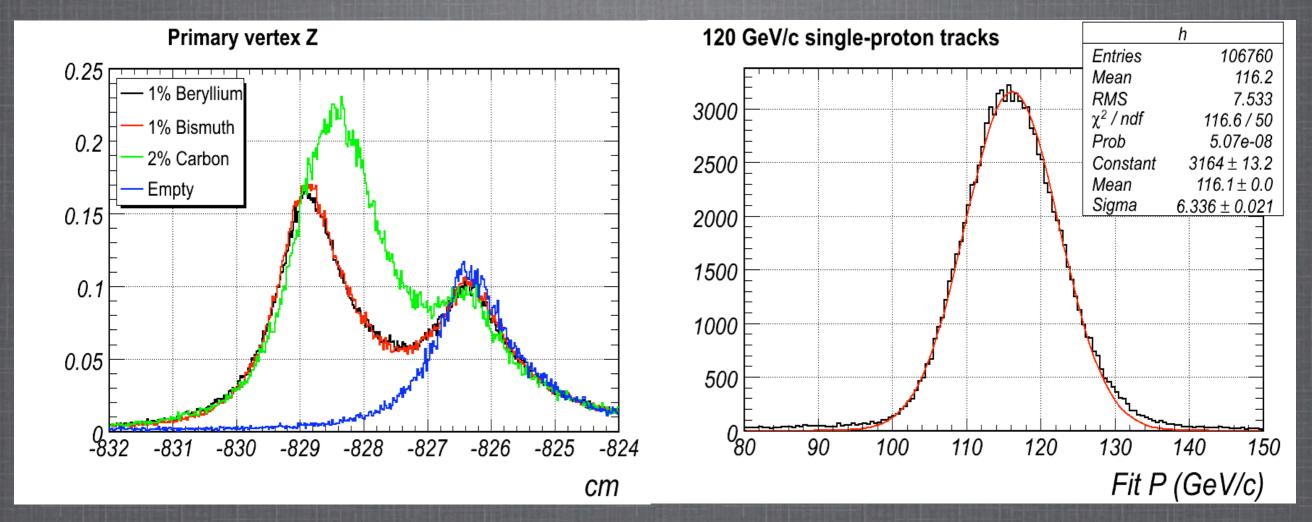
Other Analyses in the Works

- **Anti-neutrino oscillation measurements**
- **ND measurements:**
  - **Inclusive CC cross-section and structure functions**
  - **mA extraction from quasi-elastic events**
  - **NC coherent scattering on Fe**
  - **Cosmic rays**

Conclusions

- **2007-08 has been a very productive year for MINOS!**
- **Latest ν_μ CC analysis results (3.36×10^{20} POT):**
  - **$\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL),**
  - **$\sin^2(2\theta) > 0.90$ (90% CL),**
  - **Decay and decoherence models disfavored at 3.7 and 5.7 σ respectively.**
- **NC analysis results (2.46×10^{20} POT): fraction of disappearing NC events < 0.17 at 90% CL.**
- **Great progress in understanding the backgrounds and systematics in the νe appearance measurement; first results are expected later this year.**
- **Results from MIPP expected later this year, expected uncertainty on ν flux is ~15%.**
- **Many ND ν interaction measurements also expected later this year.**
- **Thanks to FNAL AD, CD, and administration for all their hard work and support!**

Backup Slides
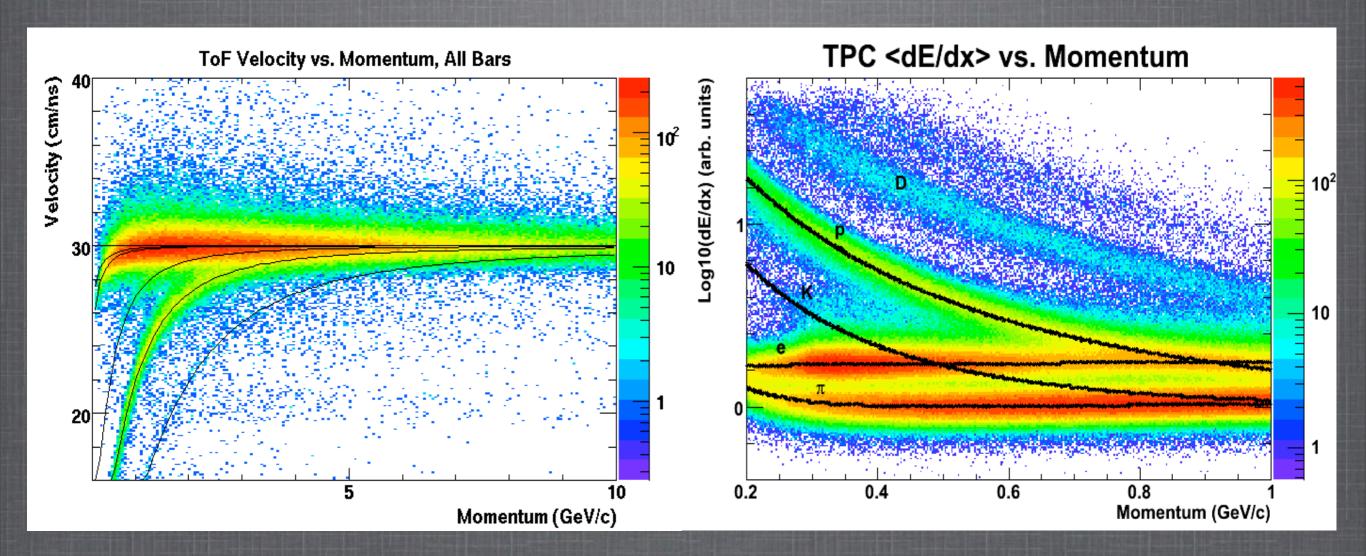
MIPP Performance

- **Momentum resolution is ~5% at 120 GeV/c, much better at lower momenta.**
- **Vertex resolution is ~8 mm in the beam direction, ~2 mm transverse.**
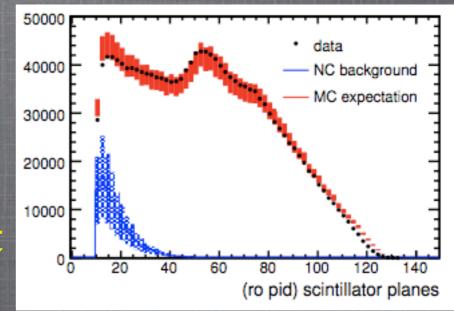- **Reconstructed momentum appears to be systematically low by ~2%.**
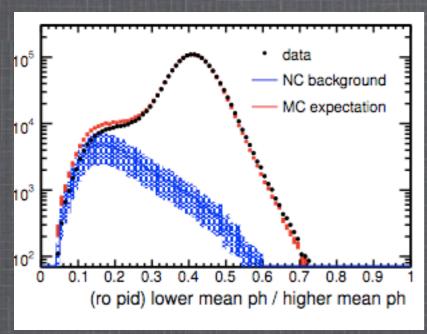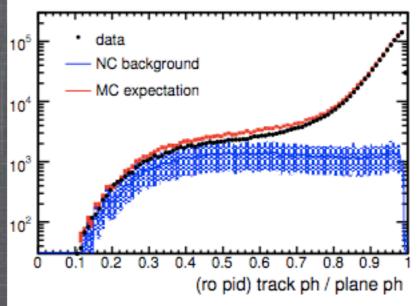
MIPP Performance

- **Ckov has ~5 pe per β=1 particle.**
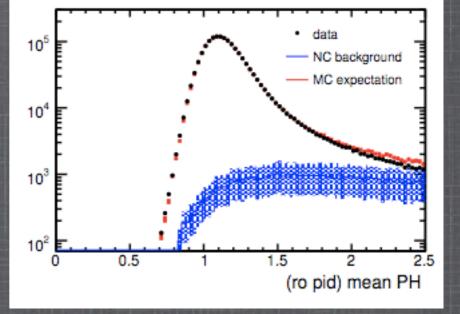- **ToF resolution is ~300 ps**
- **TPC <dE/dx> resolution is ~12 %.**

ν$_\mu$ CC/NC Separation

- **CC/NC separation achieved via a kNN event selection based on:**
  - **Track length**
  - **Mean pulse height**
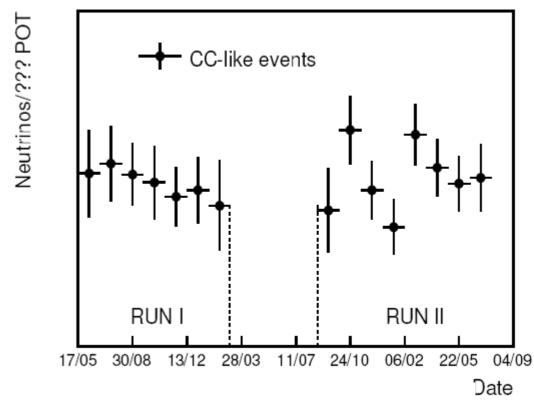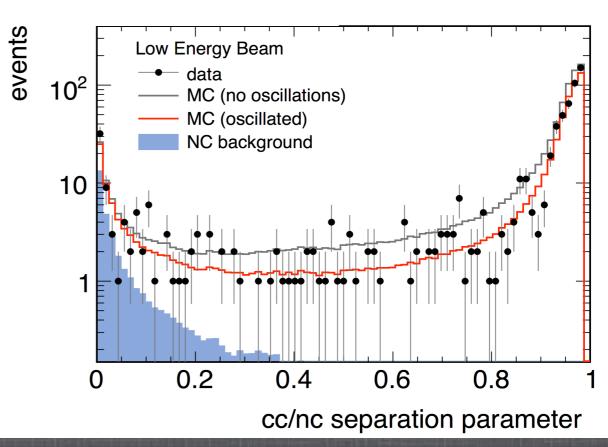 - **Fluctuation in pulse height**
  - **Transverse track profile**
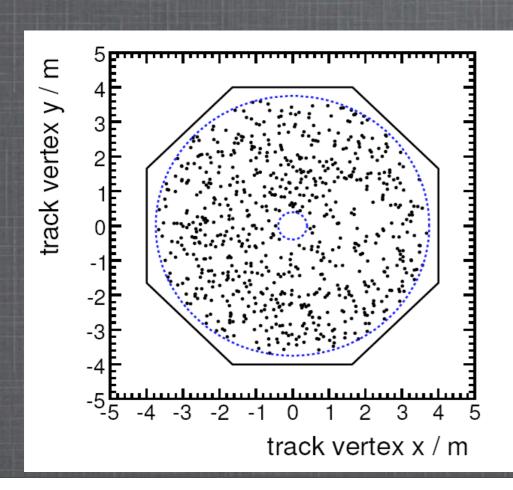
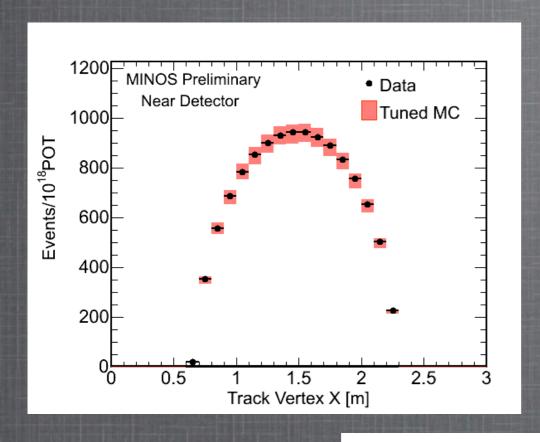# Far Detector Low-level Data Quality Checks

- **FD energy spectrum is only looked at after performing:**
  - **low-level data quality checks**
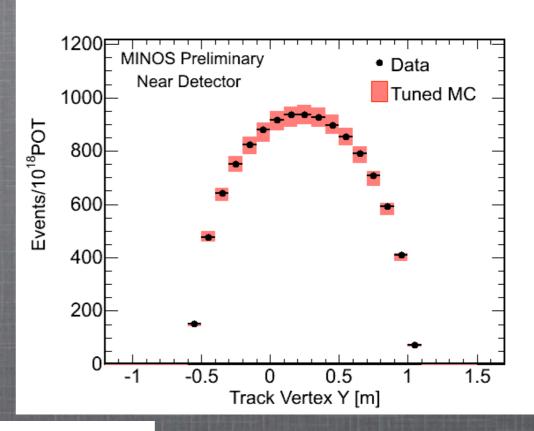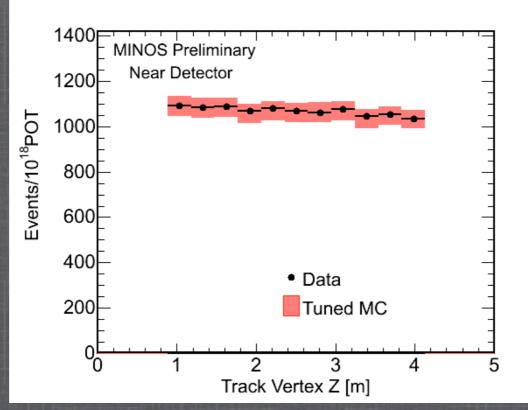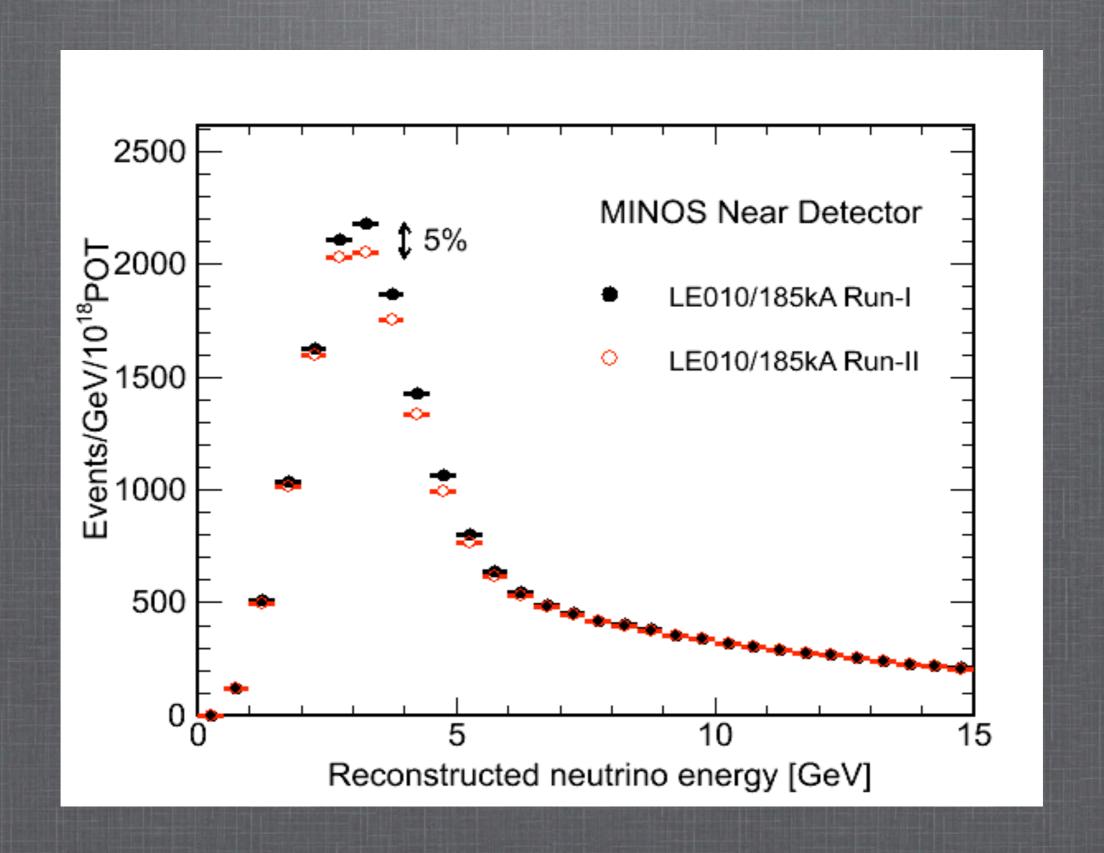 - **procedural checks**

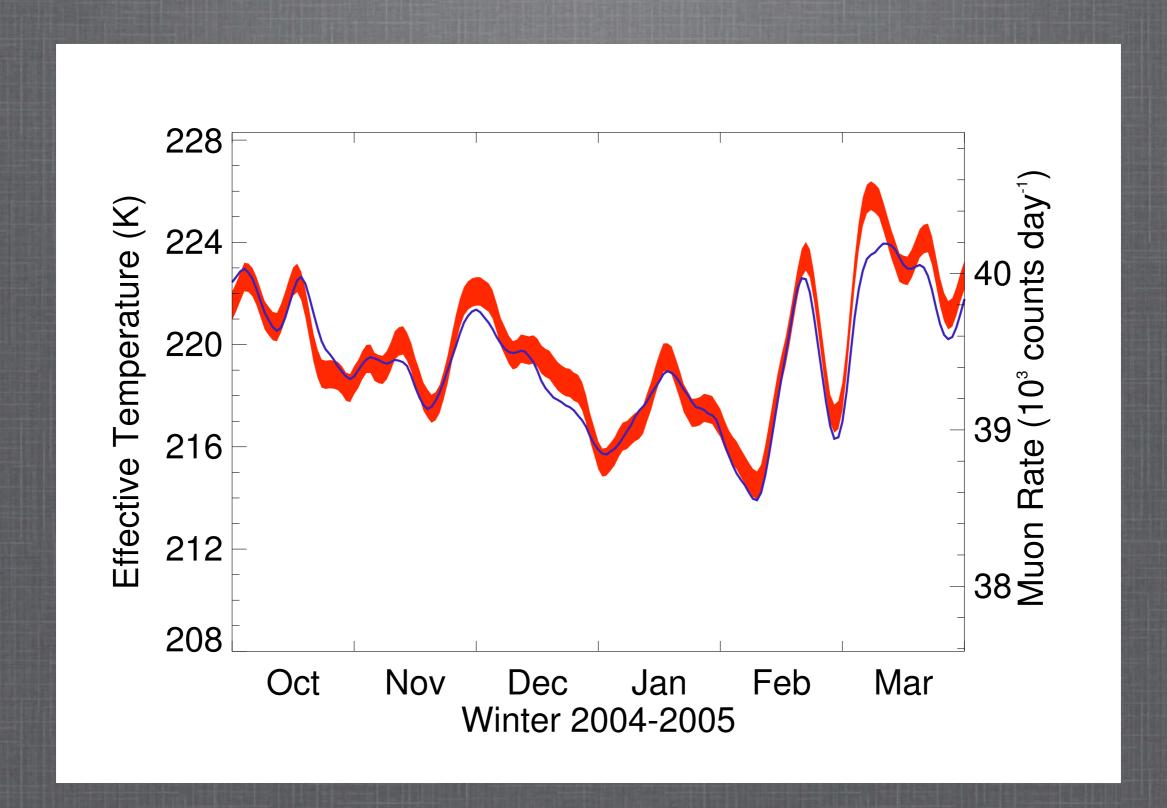# ND Distributions After Making PID Cut

LE1 vs. LE2 Beam Configurations

Sudden Stratospheric Warmings

QUESTIONS I HAVE

• Can someone remind me why the best fit value on the top (small) plot on slide 17 has $\sin^2(2t) > 1$? Is it just statistics? This plot was made with MC...

• Will the NC result be redone with our latest values of dm^2 and $\sin^2(2\theta)$?

• Should I mention the Horn 1 problem?

• Can I mention the Nature article submission?

NOTE:

• I intend to add more backup slides, but if you have any specific suggestions, please let me know!